DARPA PROJECT FINAL REPORT

PROJECT TITLE: Fabrication of a Terahertz Imaging System

PRINCIPAL INVESTIGATORS: Profs. James Kolodzey and Keith Goossen

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REPORT NUMBER: Final Progress Report

REPORTING PERIOD: September 30, 2003 to September 29 2004

OBJECTIVE: Demonstration of a THz imaging system, constructed using commercial components and devices fabricated at the University of Delaware

DARPA Program Managers:
Doug Kirkpatrick
Frank Patten

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PROJECT INFORMATION

(1) Overall Status:

During this project, the work on the development of a Terahertz imaging system was performed in the labs of both Prof. Kolodzey and Prof. Goossen. The terahertz and optical components for generating, detecting and manipulating the terahertz beams were designed, developed, and purchased. To evaluate suitable materials for lenses and components, spectra were measured by the technique of Fourier transform infrared spectrometry, using a Thermo-Nicolet 780 system. This FTIR system operates over a frequency range from 0.6 THz to 300 THz (20 to 10,000 cm-1). Spectral transmission measurements for lens materials such as ZnSe, and for architectural materials such as dry-wall (Sheet Rock) were obtained. The development and characterization of a prototype imaging system using a CO_2 gas laser source at 28.3 THz (10.6 μm wavelength), and a pyroelectric multipixel video cameral with a broad spectral response in the THz region was demonstrated. An optical system to expand and collimate the beam using ZnSe lenses was designed and assembled on an optical bench. All of these components were operated at room temperature. This optical delivery system enabled the measurements of the transmission and reflection of objects placed in the terahertz beam path. The arrangement of this terahertz imaging systems was modular in the sense that alternative sources and detectors can be substituted for comparisons of performance, and for operation in difference spectral regimes. Penetration, or see-through, images of a series of objects and materials, including circuit boards, carbon nanotubes, printing ink, DNA, clothing textiles, and animal bone were made and analyzed. We found that the lower terahertz frequencies (0.6 to 3 THz) offer a greater degree of penetration through architectural and textile materials; whereas the upper terahertz frequencies (2 to 10 THz) offer spectral selectivity by having specific spectral lines. We evaluated the operation of this Terahertz imaging system, and assessed the suitability of Terahertz frequencies for see-through imaging compared to other frequencies. We conclude that the operation of a terahertz imaging system is feasible with components that can either operate directly at room temperature, or that can be cooled thermoelectrically so that they operate in a room temperature environment without the need for liquid cryogens.

(2) Developments and Accomplishments:

1. Terahertz sources. (a) The CO_2 laser that was chosen as the initial source of THz radiation was manufactured by Access Laser Company (model Lasy4). The emitted wavelength could be tuned between 10.3 µm - 10.8 µm (corresponding to frequencies of 29.1 to 27.8 THz) with a constant average power output of 400 mW. The convenient features of this laser were its small physical size(300 mm X 70 mm X 63.5 mm) and the air-cooling system which accounted for its easy operation. The typical beam diameter of the laser was 3 mm.

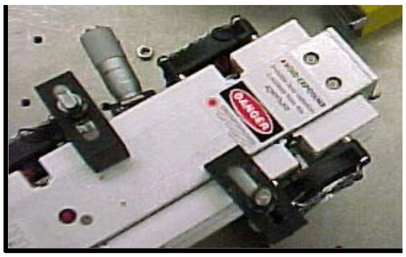

Figure 1. Top view of THz source based on CO_2 laser.

(b) For the lower THz frequencies, we developed a SiC based source that operates at 7 to 11 THz, with peak output power up to 0.3 milliWatt, and device operating temperatures up to 150 K, which is accessible by portable Stirling Cycle coolers. This SiC-based THz source, or other THz sources still under development, can replace the CO2 laser used in the prototype system.

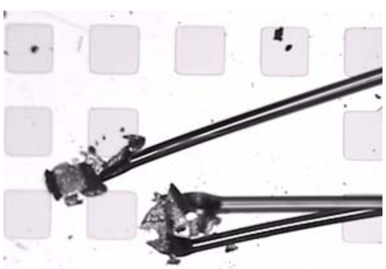

Figure 2. Top view of THz source based on SiC dopant emitter. Dark gray areas are active semiconductor; lighter shiny areas are surface metal contacts.

2. Terahertz detectors. (a) The detector for the imaging setup was a wide band pyroelectric detector (Scientech Inc. Model No. PO5). The wavelength of operation of the detector extends from 300 nm to 25µm. As the sample was translated across the laser beam, the detector produced an electrical voltage depending on whether or not the beam was obscured. For our imaging system, the relative value of the output voltage versus position of the sample, provided an overall intensity profile of the object that enabled the construction of the image of the sample. The output of the detector was fed into a lock-in amplifier synchronized to the chopping frequency of the laser. To improve resolution and also to reduce the intensity illuminating the detector, the diameter of the beam was reduced by using a 0.5 mm metal aperture in front of the source.

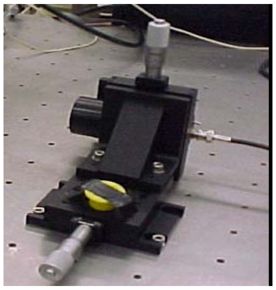

Figure 3. Pyroelectric detector mounted on x-y translation stage.

(b) To obtain multipixel THz images of objects, a thermal imaging camera (Electrophysics PV320L2) with wavelength range from 2 µm to 14 µm was used. The camera used a 15.52 x 11.64 mm array of pyroelectric detectors arranged in a focal plane to image the object. The wavelength range was limited by the ZnSe lens, not the pyroelectric focal plane array . The array consisted of 320 x 240 pixels, each of diameter 48.5 µm [11] The output of the camera was fed to a computer through an USB port. The process of data acquisition and image analysis was performed by a software package called Velocity provided by Electrophysics Inc. This software was menu driven and could record movies and still images of objects. It enabled digital control of brightness, contrast and zoom. Other notable features of this software are its ability to give a statistical representation of the temperature at various points of the image.

Figure 4. Side view of 320 x 240 pixel thermal imaging camera (Electrophysics PV320L2) used for THz imaging.

3. Terahertz imaging components and lenses.

(a) The initial THz imaging setup was designed using the CO_2 laser, the pyroelectric single pixel detector, the lock-in amplifier and the x-y-z motion translation stages. The entire process of motion and data acquisition was synchronized using the computer program written in Labview software. This setup was used to obtain images of samples in the transmission and reflection mode. In the transmission mode, the pyroelectric detector was initially aligned with the laser to observe the maximum signal. The sample to be scanned was then placed in a line of sight between the laser and the detector, and aligned so that the sample could be scanned within a range of 20 mm x 20 mm, limited by the translation stages. While the sample was being scanned, the detector recorded the signal intensity, and correspondingly produced a high or low voltage for each position of the sample. These voltages were recorded in a Microsoft Excel spread sheet producing a table of voltage profiles for the different points on the sample. The THz image of the sample could then be extracted from the Excel sheet by using scientific plotting software (Origin 6.1). A photograph of the transmission mode setup shown in Figure 5.

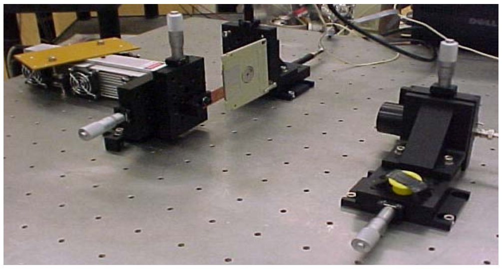

Figure 5. Photograph of the single pixel setup for THz transmission mode imaging showing the optical bench top with the laser (left), the pyroelectric detector (right) and the floppy disk sample (middle gray square) placed on the translation stages.

(b) For the imaging setup of the multiple pixel thermal imaging camera, the entire sample was illuminated by an expanded laser beam and the image was recorded by a single exposure. To avoid distortion of the image, the THz beam was expanded to the size of the illuminated sample. Thus it was necessary to design and construct a beam expansion setup. The initial problem to implement this beam expansion was to find a suitable lens material that was transmissive at the operating THz frequency. Glass, the common material used for optical applications, has a high absorption at THz frequencies.. The lenses that were finally chosen were ZnSe, manufactured by Laser Research Optics. At 10.6 µm, the total absorption loss of the lenses was 0.3 % [16]. The anti-reflective(AR) coating on the lenses ensured that the reflectivity at the air-ZnSe interface wais less than 0.5%.

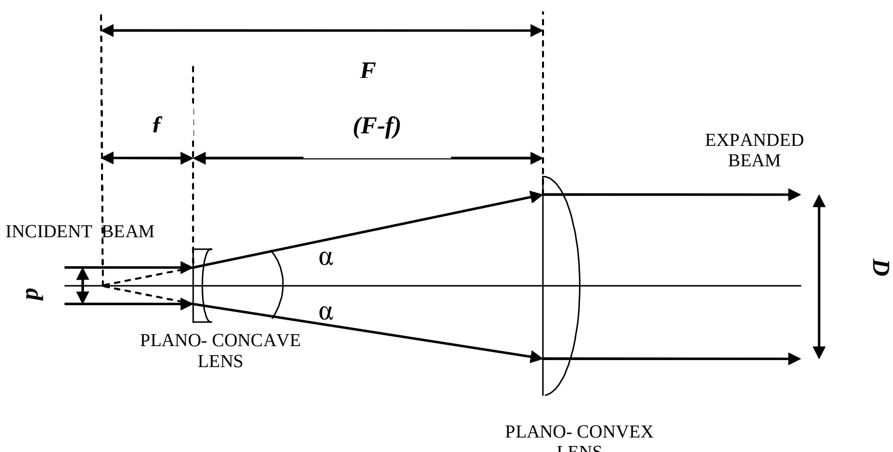

Figure 6. Schematic diagram illustrating the design of setup for THz beam expansion by dual lens system. The figure shows the relative position of plano concave lens, plano convex lens, the incident beam and the expanded beam.

To solve the optical design problem, the dual lens combination of a plano-concave and plano-convex lens was used to obtain an expanded collimated beam, as shown in Fig. 6. This design, which was based on the plano convex and plano concave lenses, reduced the spherical aberration, and produced a 20X expansion of the beam diameter. A plano concave lens of focal length 12.7 mm and diameter 9.5 mm was used as the divergent lens, and a plano convex lens was used for converging. The diameter of the plano convex lens chosen for this purpose was 63.5 mm. In the setup, the two lenses were separated by a distance of 241.3 mm so that their foci converged at the same point. The imaging setup for the beam expansion using the plano concave and plano convex lens is illustrated in Figure 7.

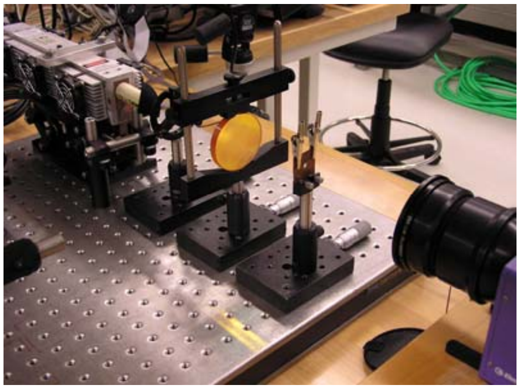

Figure 7. Schematic diagram of setup for measurement of THz beam diameter as obtained by dual lens system. The figure shows the position of the laser (upper left), plano concave lens, plano convex lens (large orange disk) and the thermal imaging camera (black lens cover at lower right).

4. Terahertz spectral absorption of materials.

THz research revolves on spectral specificity and transmission properties. THz is more selective than X-rays (300,000 THz) and is more sensitive to the nature of the materials it passes through. On the low frequency side of terahertz, millimeter waves have the disadvantage that they are generally not chemically sensitive: few substances have fingerprint spectra in the millimeter range. What's more, for imaging applications, their longer wavelength translates into poor image resolution. Oscillator strengths of the emission or absorption lines for rotational and vibrational excitations of molecules tend to increase in strength with frequency (f) as f^2 or even f^3 , and often peak in the terahertz region, giving terahertz a strong natural sensitivity advantage. On the high frequency side of the terahertz range, infrared (IR)has the disadvantage that optical scattering is proportional to f^4 so that THz has greater penetration through aerosols, clouds, and solids. Furthermore, in the IR, the molecular resonances are for light molecules such as CO_2 (1300 to 2300 cm^{-1} , i.e. 40 to 70 THz, or 7.7 to 4.4 microns). Heavy molecules such as chemical agents and biomolecules, however, resonate at THz frequencies.

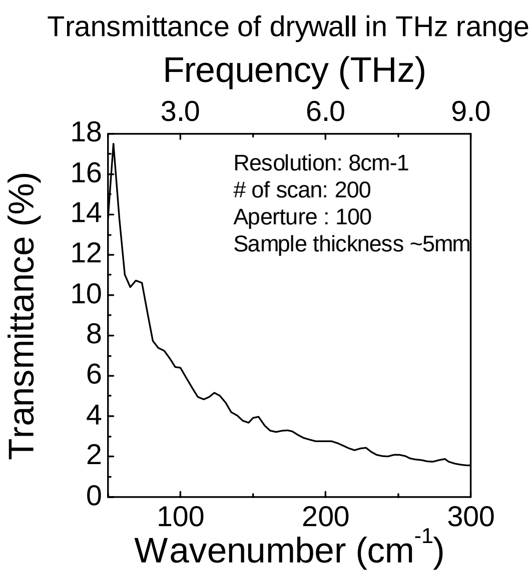

Figure 8. Example of penetration imaging in the terahertz range. Left plot shows measurement of transmission through architectural drywall (Sheetrock), demonstrating feasibility of THz penetration scanning. The transmittance above 1 % is sufficient for THz imaging using sources with output powers in the 100 microwatt range, and with available detectors.

In the 4 to 25 THz range, doped silicon emitters are the only source technology. They can be used with bolometer and with Merc-Cad-Telluride detectors. This THz range provides strong resonance with bio chemicals for identification.

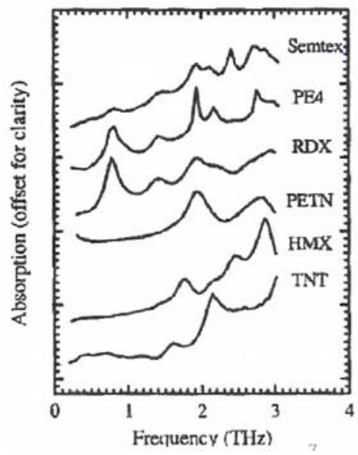

Figure 9. Spectral features of explosive chemical agents. Note that the distinguishing spectral features appear at frequencies above 0.8 THz. M. C. Kemp, SPIE 5070 (2003); see also M.G. Allen Physical Sciences Inc. (www.psicorp.com).

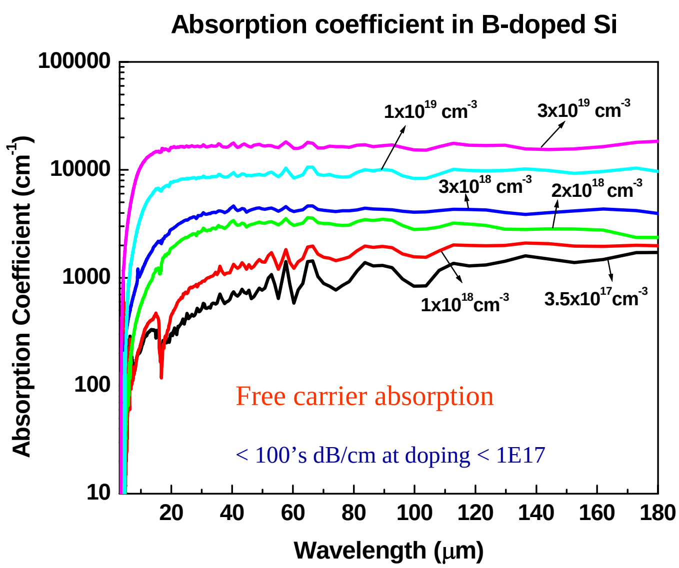

Figure 10. Absorption in the THz range of silicon versus doping concentration. With increasing wavelength, not that the absorption does not continue to increases indefinitely with λ^2, but saturates. The limited absorption means that doped devices do not absorb excessively and are practical for THz operation. feasible (S. Ray & J. Kolodzey, J. Appl. Phys., v. 95, May 2004). Note that 100 μm corresponds to 3 THz.

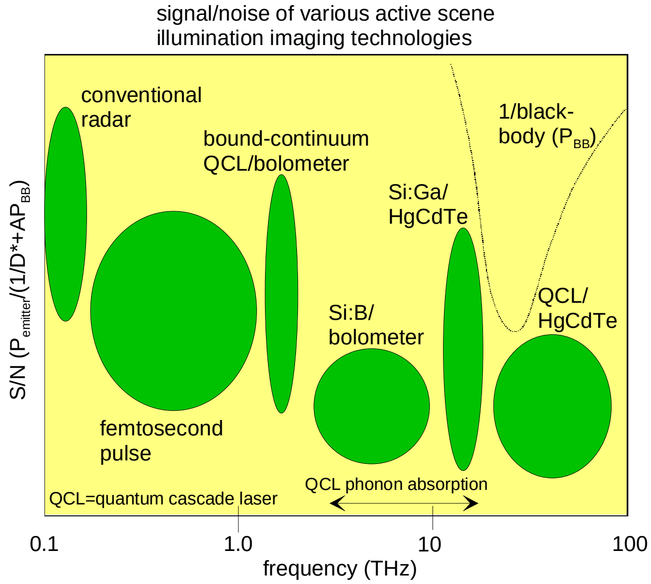

Figure 11. Plot of signal to noise ratio for source/detector combinations over different spectral ranges, showing advantages of Active Terahertz Imaging compared to other technologies.

5. Terahertz imaging of materials.

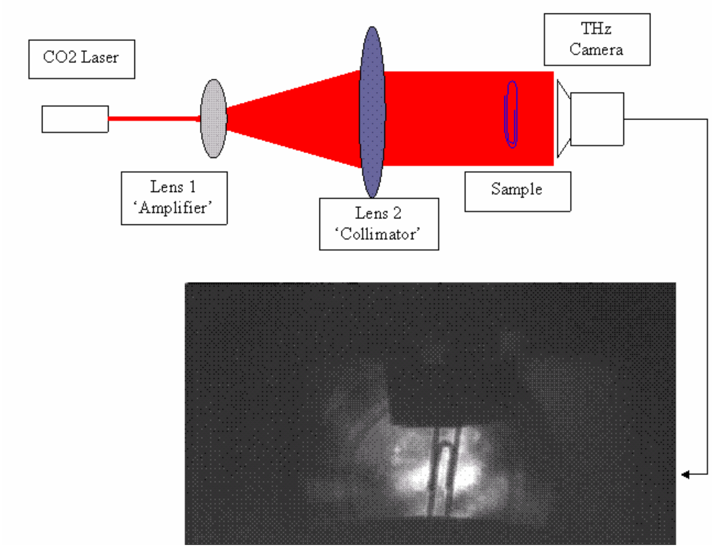

Figure 12. Demonstration of UD lab THz camera system: transmission Image Of Paper Clip Behind A solid undoped Silicon Wafer

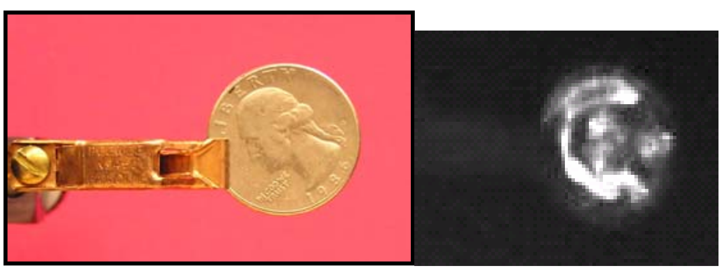

Figure 13. Reflection images of a quarter coin. Left: Visible light. Right: THz image behind a solid undoped silicon wafer.

Figure 14. Transmission image of a metal screw in a polyethylene bag, at 28.3 THz

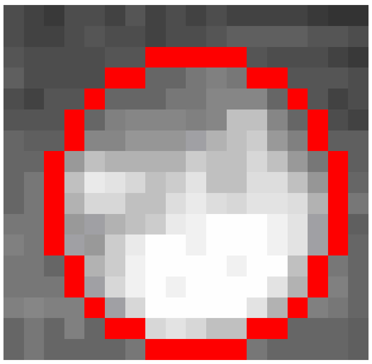

Figure 15. Transmission image of chicken egg membrane at 28.3 THz, showing has transmission through almost all of its area and is measured to be 9 microns thick. These results in conjunction with those of the bone samples suggest that the limitation of the transmission through objects in the terahertz spectrum is dependent on the frequency used.

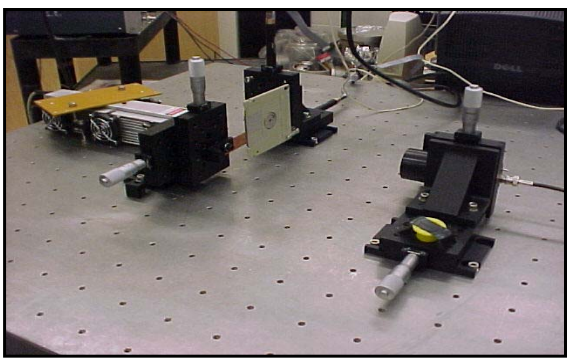

Figure 16. Setup for Terahertz imaging through printed circuit cards.

(3) <u>Problems</u>:

For many construction materials such as architectural drywall as shown in Fig xxx, the transmission increases at lower frequencies. Therefore we intend to replace the CO2 laser operating at 28 THz with a SiC based source operating at 8 THz, and by a boron doped silicon source operating below 3 THz. Additional funds are needed to assemble this lower frequency THz system.

(4) **Future Plans**:

Replace the CO2 laser operating at 28 THz with a SiC based source operating at 8 THz, and by a boron doped silicon source operating below 3 THz.

(5) **Personnel Supported with the research effort:**

Faculty:
James Kolodzey
Keith Goossen

Graduate Students
Pengcheng Lv (Kolodzey)
Paola Murcia (Goossen)

(6) **Publications:**

I.V. Altukhov, E.G. Chirkova, V.P. Sinis, M.S. Kagan, R.T. Troeger, S.K. Ray, J. Kolodzey, A.A. Prokofiev, M.A. Odnoblyudov, I.N. Yassievich, "Effect of potential and doping profiles on excitation of stimulated THz emission of SiGe/Si quantum-well structures," Physica B-Condensed Matter, v. 340-342, pp. 831-834, Dec 31 2003.

S. K. Ray, T. N. Adam, R. T. Troeger, J. Kolodzey, G. Looney, and A. Rosen, "Characteristics of THz waves and carrier scattering in boron-doped epitaxial Si and Si1-xGex films," Journal Appl. Phys., vol. 95, pp. 5301 – 5304, May 2004.

P.-C. Lv, R. T. Troeger, T. N. Adam, S. Kim, J. Kolodzey, I. N. Yassievich, M. A. Odnoblyudov, and M. S. Kagan, "Electroluminescence at 7 terahertz from phosphorus donors in silicon," Appl. Phys. Lett., vol. 84, (1) pp. 22-24, 2004.

P.-C. Lv, R.T. Troeger, T.N. Adam, S. Kim, J. Kolodzey, I.N. Yassievich, M.A. Odnoblyudov, and M. Kagan, "Terahertz emission from electrically pumped gallium doped silicon devices," Appl. Phys. Lett., v. 85 (17), pp. 3660-3662, 2004.

J. Kolodzey, T. N. Adam, R. T. Troeger, P.-C. Lv, S. K. Ray, I. Yassievich, M. Odnoblyudov, and M. Kagan, "Terahertz emitters and detectors based on SiGe nanostructures," International Journal of Nanoscience, vol. 3, nos. 1 & 2, pp. 171-176, 2004.

"Surface terahertz emitter based upon impurity transitions," P. Salazar and K.W. Goossen, 2004, in press.

P.-C. Lv, R. T. Troeger, S. Kim, S. K. Ray, K. W. Goossen, and J. Kolodzey, I. N. Yassievich and M. A. Odnoblyudov, "Terahertz emission from electrically pumped gallium doped silicon devices," Appl. Phys. Lett., vol. 85, pp. 3660-3662, 2004.

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P.-C. Lv, R.T. Troeger, T.N. Adam, S. Kim, J. Kolodzey, I.N. Yassievich, M.A. Odnoblyudov, and M. Kagan, “Terahertz emission from electrically pumped gallium doped silicon devices,” Appl. Phys. Lett., v. 85 (17), pp. 3660-3662, 2004.

J. Kolodzey, T. N. Adam, R. T. Troeger, P.-C. Lv, S. K. Ray, I. Yassievich, M. Odnoblyudov, and M. Kagan, “Terahertz emitters and detectors based on SiGe nanostructures,” International Journal of Nanoscience, vol. 3, nos. 1 & 2, pp. 171-176, 2004.

P.-C. Lv, X. Zhang S. Kim, J. Kolodzey, A. Powell, “Terahertz emission from electrically pumped silicon carbide devices,” manuscript in preparation for submission to Nature Materials, 2005.

(7) <u>Interactions/Transitions:</u>

a. Participation/presentations at meetings, conferences, seminars, etc.

Twelfth International Workshop on The Physics of Semiconductor Devices 16-20 Dec., 2003, Chennai, India. (invited talk)

National Laser Symposium 2003, 22-24 Dec., 2003, Kharagpur, India. (invited talk)

2004 International Microwave Symposium, Fort Worth, Texas, June 6-11, 2004, IMS2004 Technical Digest.

First IEEE International Conference on Group IV Photonics, Hong Kong, 29 Sept. 2004. (invited talk)

12th International Symposium on Ultrafast Phenomena in Semiconductors, Vilnius, Lithuania, 22 Aug. 2004, (invited talk)

SPIE Optics East Conference on Semiconductor and Nanotechnologies and Applications; Nanosensing: Materials and Devices, Philadelphia, 25–28 October 2004; (invited talk)

2004 Lester Eastman Conference, Rensselaer Polytechnic Institute, August 4-6, 2004, International Journal of High Speed Electronics and Systems.

6th International Conference on Mid-Infrared Optoelectronic Materials and Devices, St Petersburg, June 28 -- July 02, 2004.

2004 IEEE LEOS Annual Meeting, Conference Proceedings, 7-11 November 2004, Westin Rio Mar Beach, Rio Grande, Puerto Rico (invited talk on Arrayed Optoelectronic Modules)

b. Consultative and advisory functions to other laboratories and agencies.

During the course of this program, the following interactions took place:
Exchange of samples with T. Adam of IBM Corporation for studies of dopants in Si
Miron Kagan (IRE, Russian Academy of Science, Moscow); Irina Yassievich and Maxim Odnoblyudov (Ioffe Institute, St. Petersburg)
Scott Simon of University of Pennsylvania medical school for bone scans
Greg Gonye of Thomas Jefferson Medical School in Philadelphia for DNA scans
Meetings with engineers from W.L. Gore & Associates regarding THz device products
Judson Technologies has agreed to provide an MCT detector for imaging

c. Transitions. cases where knowledge resulting from effort is used:

Discussions on terahertz imaging and sensing with Dr. K. Roe, chief technical officer of Smiths Detection Corp., manufacturer of x-ray scanners for airports.

(8) New discoveries, inventions, or patent disclosures:

2 patents:
1. Terahertz Frequency Radiation Sources And Detectors Based On Group Iv Materials And Method Of Manufacture, J. Kolodzey, S. Ray, T. Adam, P. Lv, T. Troeger, M. Kagan, I. Yassievich, M. Odnoblyudov, (Ser. No. 60/461,656), Filed April 9, 2004.

2. Terahertz Frequency Band Wavelength Selector, J. Kolodzey, T. Adam, D. Prather, (Ser. No. 10/820,517), Filed April 8, 2004.

(9) Honors/Awards:

James Kolodzey has been appointed Charles Black Evans Professor in Electrical Engineering in recognition of record as scholar, teacher and for service to the University of Delaware, Oct. 1, 2004, (http://www.udel.edu/PR/UDaily/2005/oct/namedprof100104.html)